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2nd Harmonic RF for the Bunch Rotation in the Fermilab Booster

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Abstract: Here we investigate the use of 2nd harmonic RF system which operates at about 106MHz to improve the bunch rotation of the Booster just before beam extraction to the Recycler Ring for slip stacking. The simulation demonstrates that use of 2nd harmonic rf along with the fundamental harmonic rf system certainly allows us to provide better quality beam to the Recycler at higher beam intensities and even at 60% larger longitudinal emittance than currently being provided.

We have investigated a possibility of using the 2nd harmonic rf system in the Booster for bunch rotation before the beam transfer to the Recycler. For slip stacking the Recycler demands about a frequency difference of 1200 Hz in RF frequency (symmetric to the central frequency) between two trains of bunches which are slipping relative to one another. This corresponds to an energy difference of ~18 MeV. (This assumes a beam delivery rate of 15Hz from the Booster.) So, for efficient slip stacking the rms energy spread of the beam from the Booster needs to be less than about 3 MeV. Operationally, we are delivering about 4.5E12 protons per cycle (ppc) achieving an average rms energy spread of about 3 MeV with ~0.1 eVsec/bunch. Currently Booster is using bunch rotation in single harmonic rf system that operates at ~53MHz. As the beam intensity per bunch increases during PIP+ era and during the PIP-II era it is highly likely that the longitudinal emittance per bunch might also go up. Under this scenario, the bunch rotation in single harmonic rf system may not be optimal. Therefore, we propose to use a 2nd harmonic rf system to linearize the rf voltage waveform during bunch rotation and reduce the energy spread of the output beam significantly even for increased beam emittance. The simulations presented below represents the overall gain due to the use of the 2nd harmonic rf system along with the fundamental accelerating rf system.

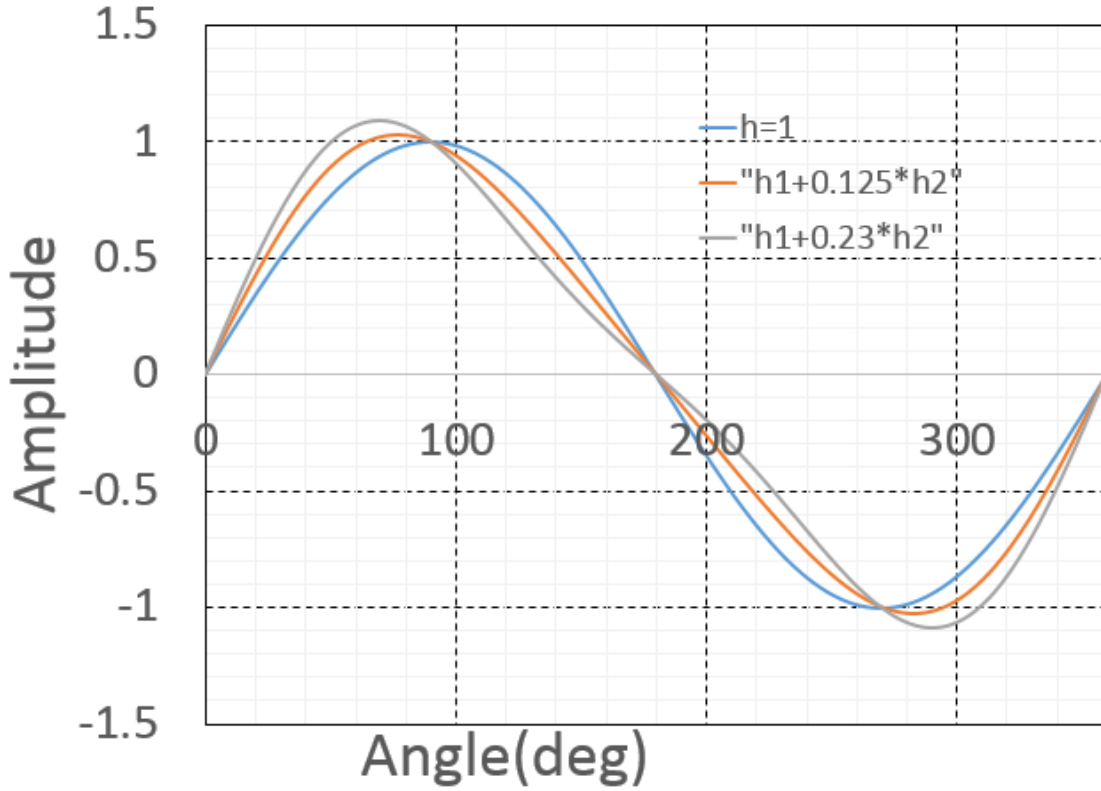


Figure 1: This displays rf linearity at the origin with $h=1$ case and $h=1+h=2$ cases for two different amplitude ratios. Amplitude along the ordinate is in arbitrary units.

The Fig.1 shows the rf wave form with $h=1$ compared with $(h=1)+(h=2)$ for two different amplitudes of $h=2$. Ideally the best linearity at the origin is obtained for a combination of $VRF(h=2)/VRF(h=1) = 0.125$. However, in reality that ratio may not be optimal for efficient bunch rotation. We have investigated various values of $VRF(h=2)/VRF(h=1)$ in longitudinal beam dynamics simulations using ESME code. We find that a ratio of ~ 0.23 gives better results for the beam emittance scenarios we are interested in.

We have investigated beam longitudinal emittance in the range of 0.1 to 0.16 per 53 MHz bunches. If the bunch emittance is far better than 0.1 eVs then bunch rotation in $h=1$ yields necessary, beam energy spread for the Recycler. However, if longitudinal emittance of the Booster beam at extraction start deviating from about 0.1 eV sec then addition of $h=2$ system helps significantly.

Booster is an RCS synchrotron operating at 15 Hz. Its accelerating magnetic field is

sinusoidal in shape without any flat top at its extraction energy of 8 GeV. However, for synchronous beam transfer to the Recycler we turn off the acceleration at about 3 ms before the extraction – the frequency is held constant and locked to the Recycler (private communications Craig Drennan). During this time beam moves somewhat inside as magnets are ramping during the rest of the cycle. Since the beam size is small enough this motion is generally not an issue. In the current operational scenario, there is a VIMAX jitter which makes beam to move radially in and out somewhat randomly. At the moment, an effort is being made to reduce this jitter.

A 53 MHz rf system is used for beam acceleration from 400 MeV to 8000 MeV and perform bunch rotation at the end. A typical case of simulated phase space distribution after bunch rotation, if we apply *snap* bunch rotation, is shown in Fig. 2. This shows that one can get an rms energy spread <3 MeV for a 0.1 eVs beam bunch. These simulations assume no tail particles arising from transition crossing in the Booster. In reality even though one can achieve 95% longitudinal emittance ~ 0.1 eV sec at the end of beam acceleration 100% emittance will be considerably larger in the Booster.

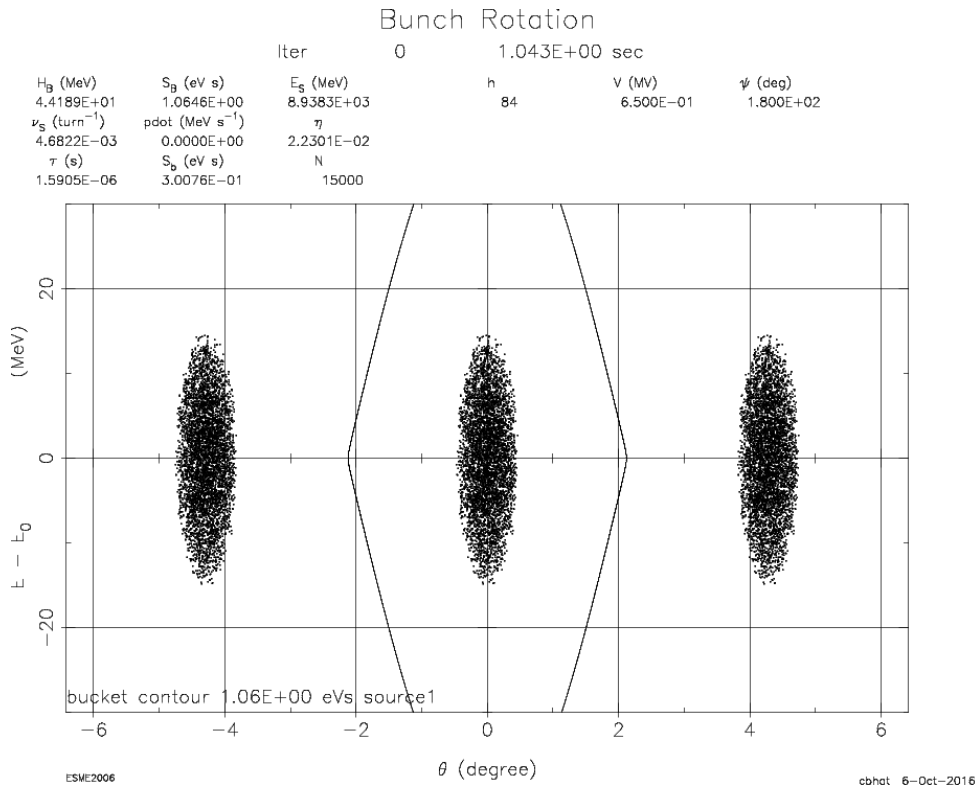


Figure 2a: Simulated phase space distribution for 0.1 eVs beam before bunch rotation.

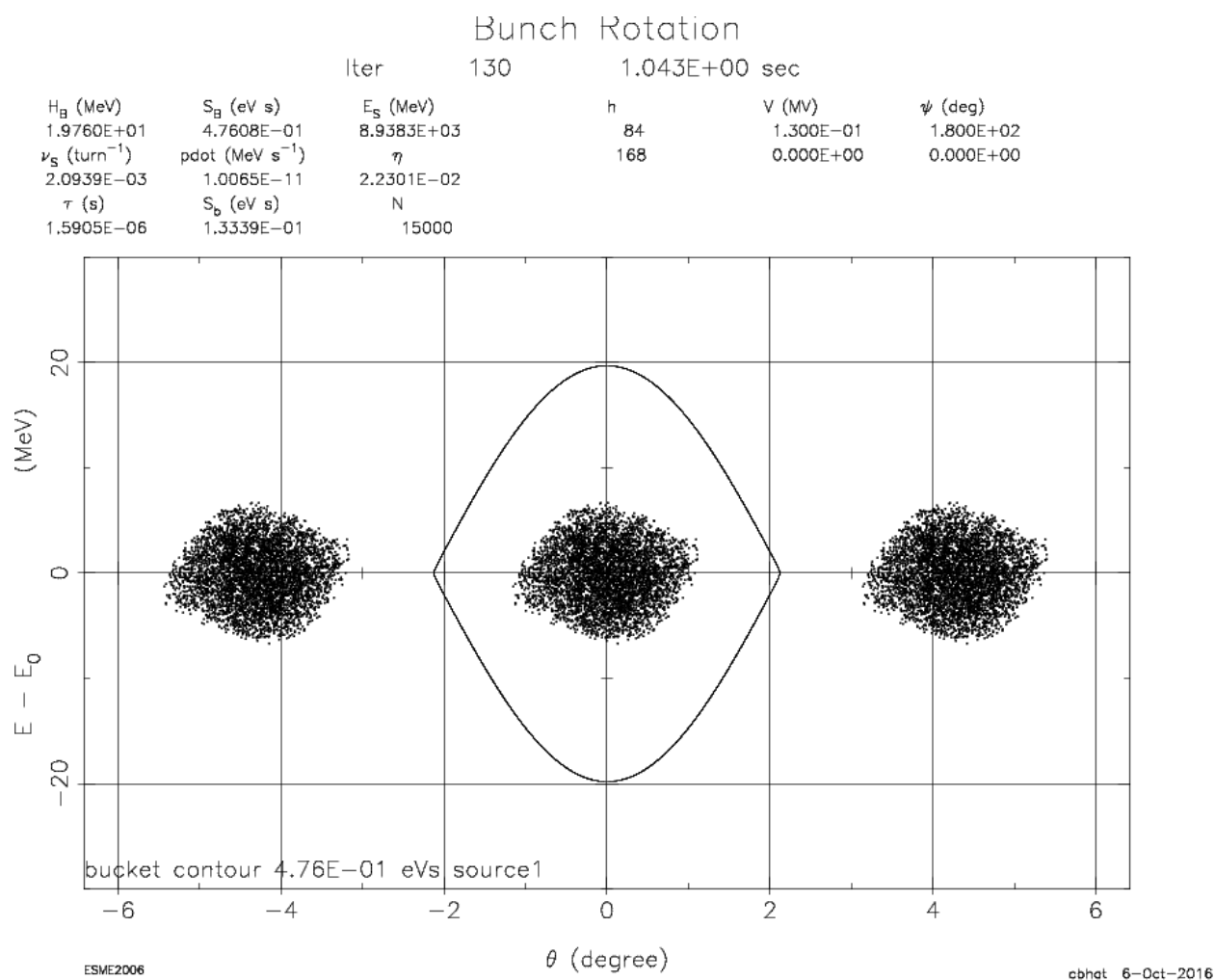


Figure 2b: After snap bunch rotation at 8 GeV just before extraction.

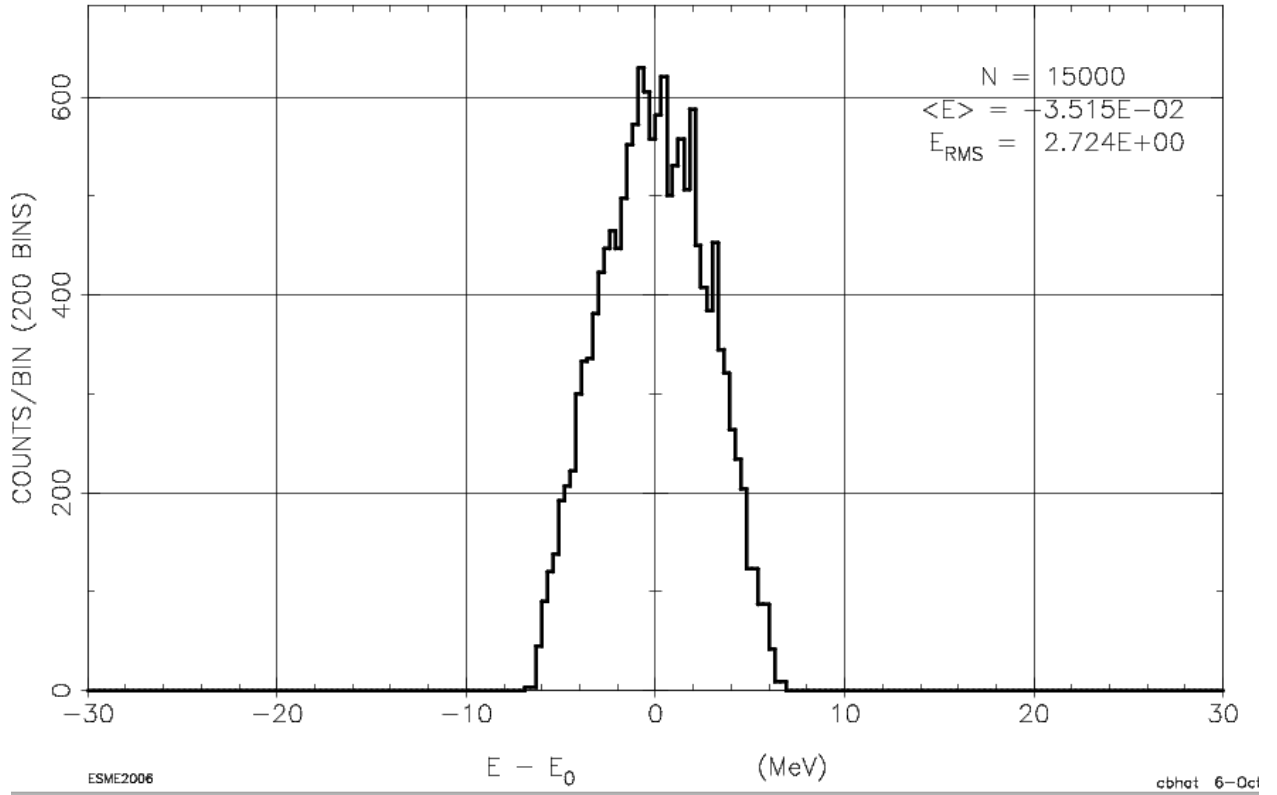


Figure 2c: The energy projection. rms beam energy spread= 2.7 MeV

Figure 3 shows for similar beam initial conditions but for bunch rotation with $VRF(h=2)/VRF(h=1) \sim 0.23$. The final energy spread is about 20% smaller than the one with $h=1$ only. In operation a gain of 20% makes a big difference in slip stacking efficiency and beam losses in the Main Injector and Recycler rings.

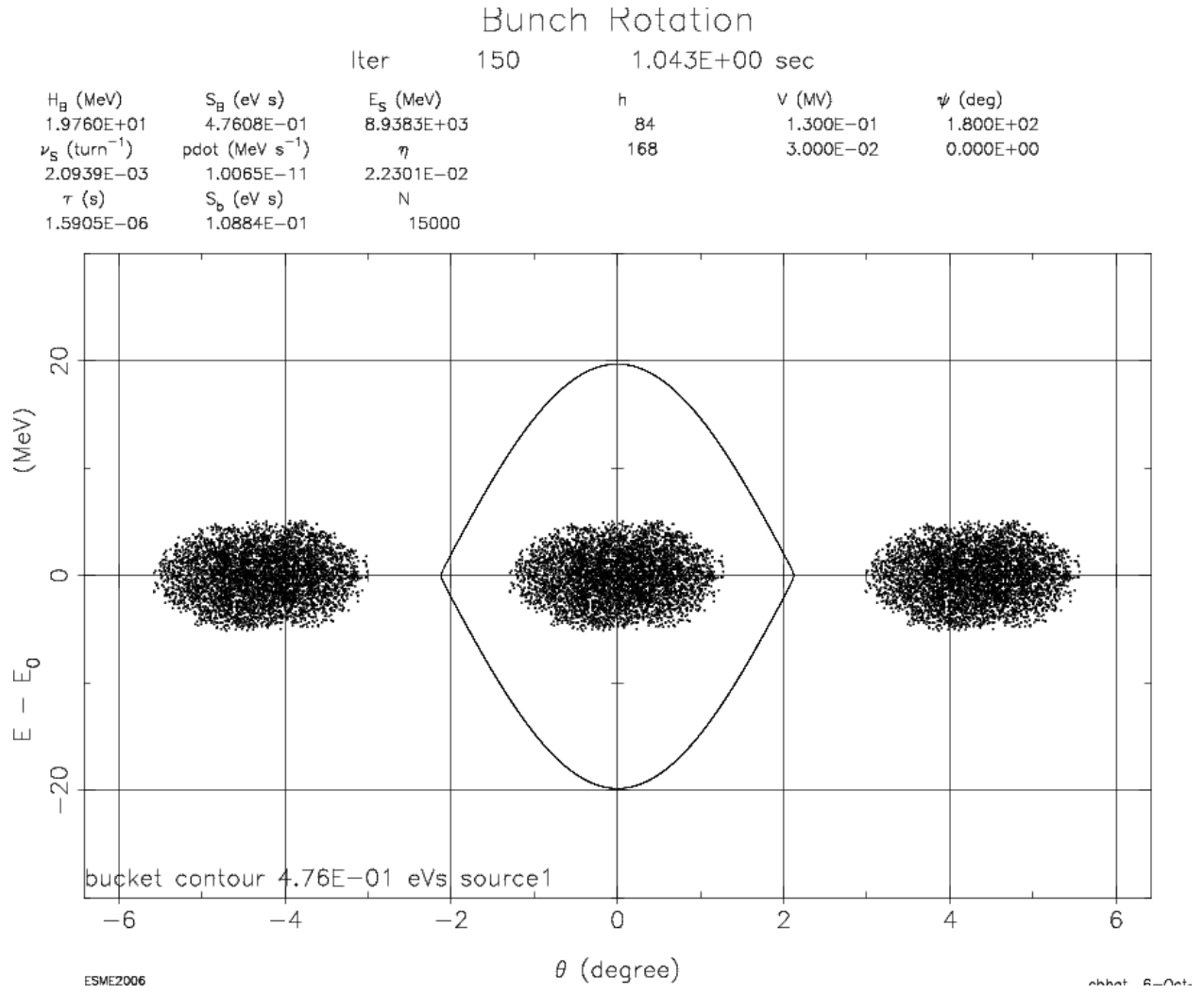


Figure 3a: After snap bunch rotation at 8 GeV just before extraction with VRF($h=2$)/VRF($h=1$) ~ 0.23 .

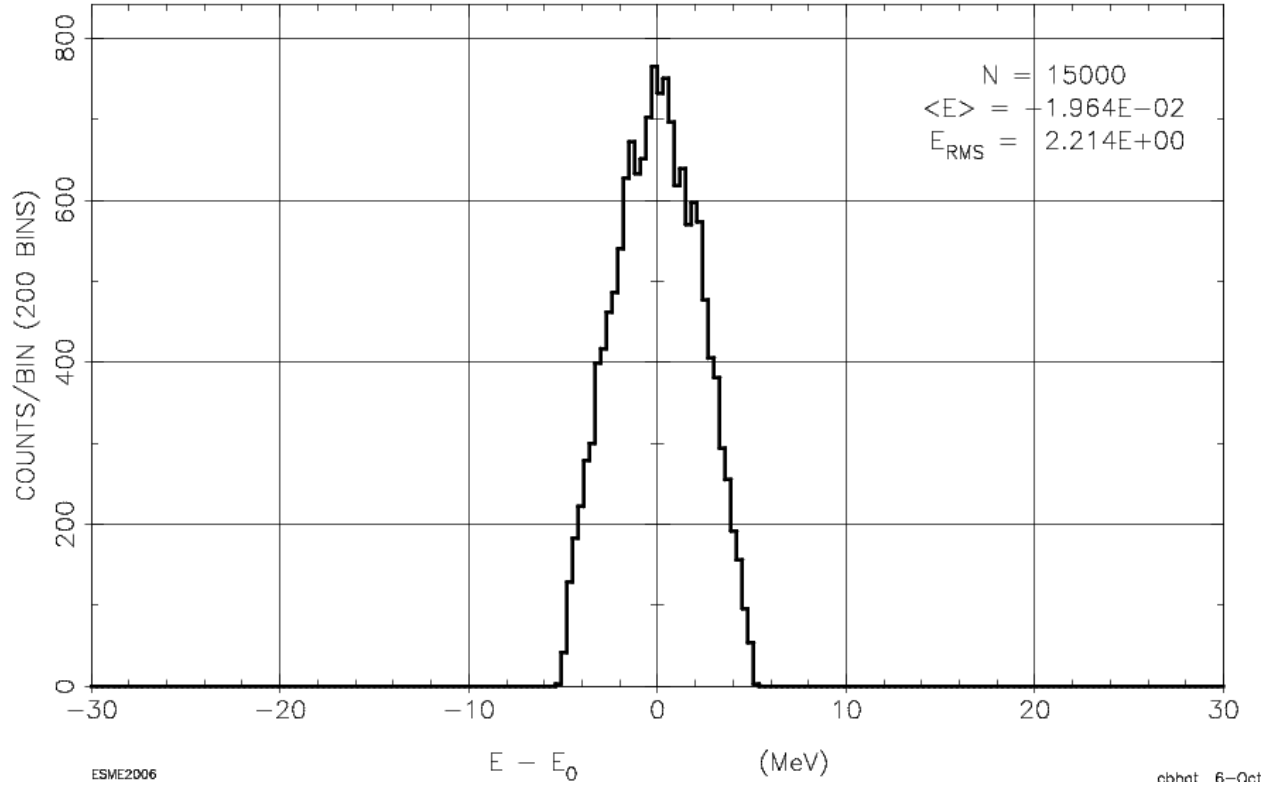


Figure 3b: The energy projection. rms beam energy spread= 2.2 MeV

Figure 4 shows simulation results for 0.16 eVs bunches for bunch rotation using h=1 and h=1+2 systems with voltage ratio of $VRF(h=2)/VRF(h=1) \sim 0.23$. We observe a significant advantage of use of h=2 system along with h=1 system.

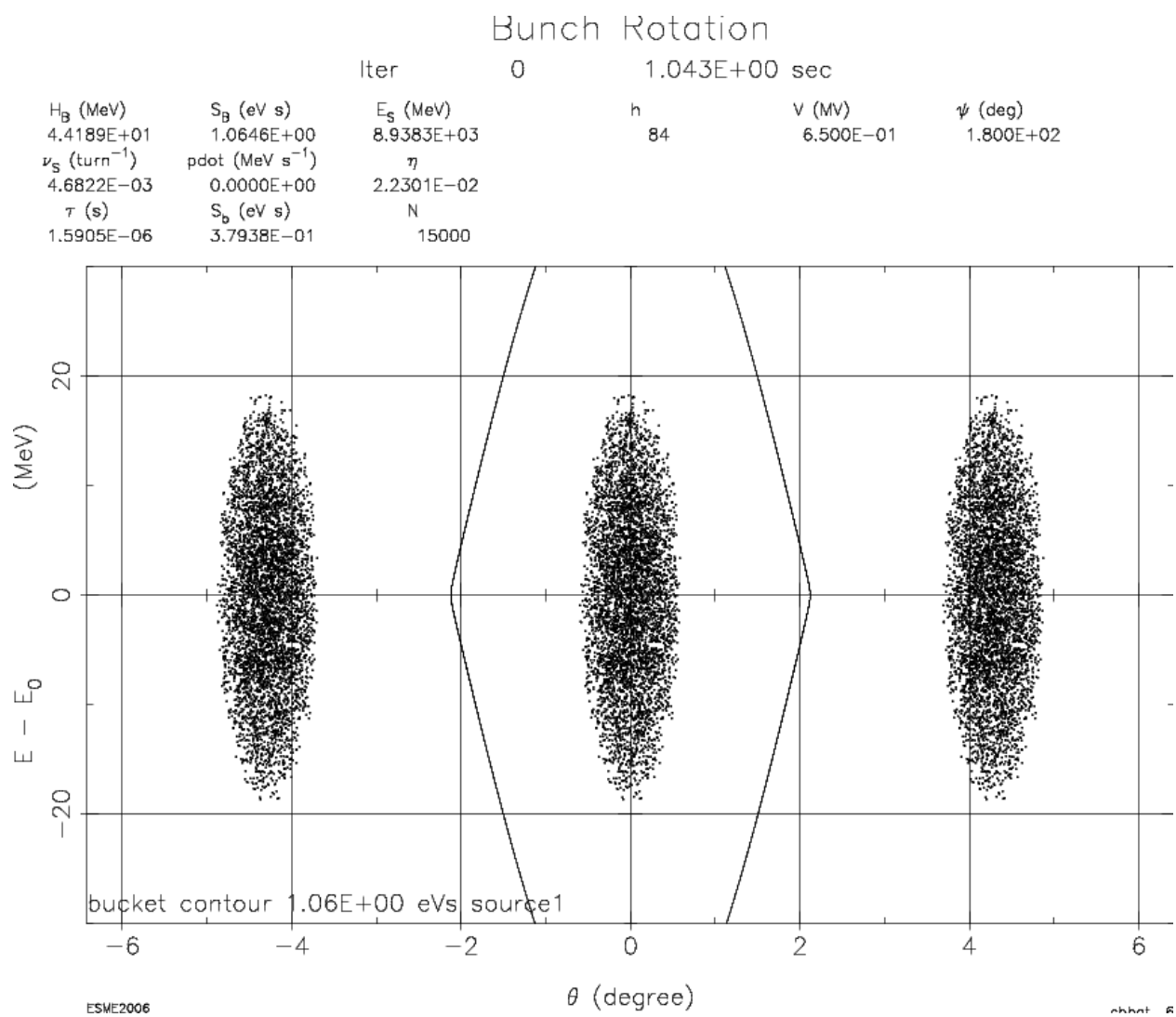


Figure 4a: Simulated phase space distribution for 0.16 eVs beam before bunch rotation.

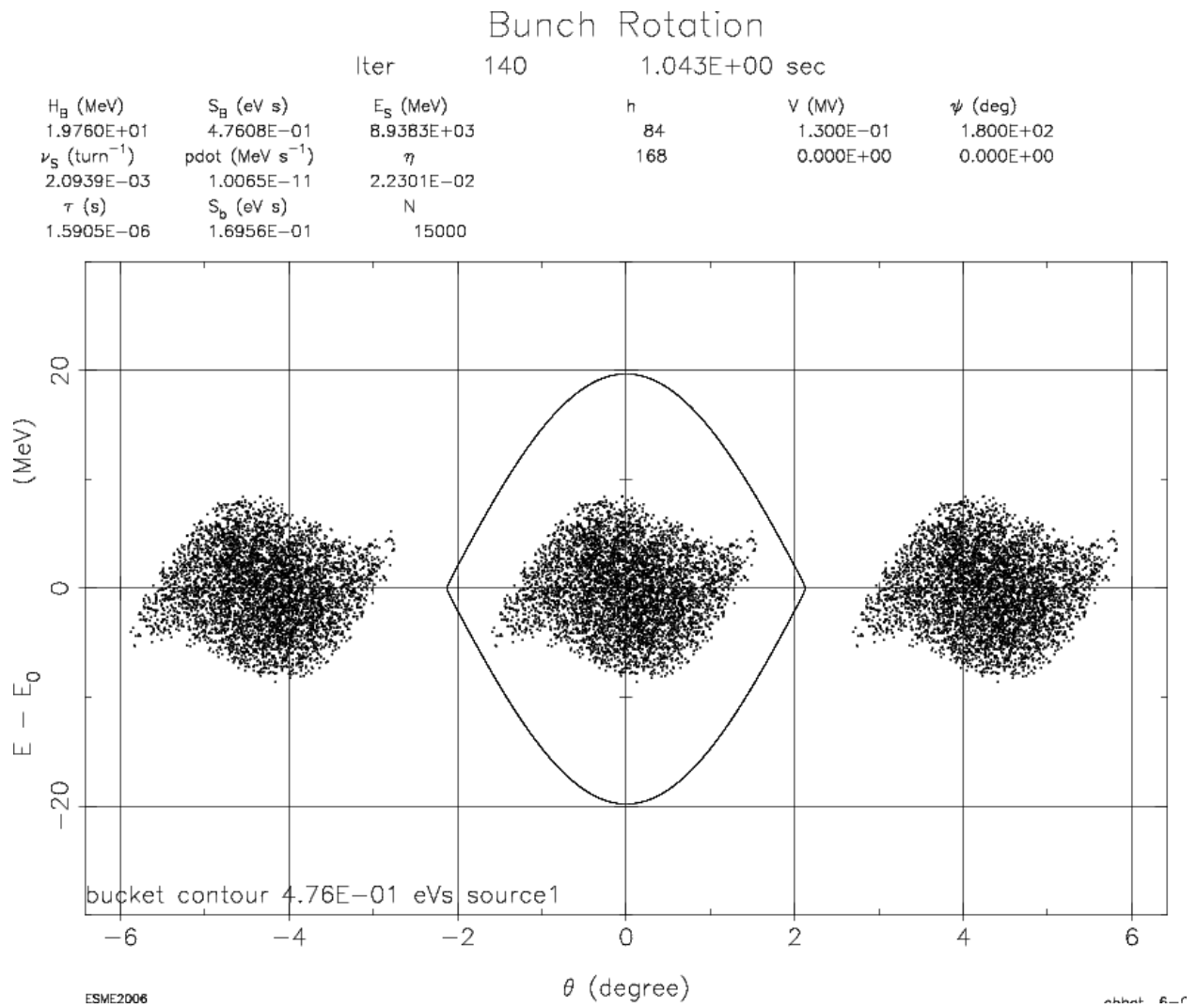


Figure 4b: Bunch rotation using $h=1$ system only. Rms energy spread = 3.44 MeV

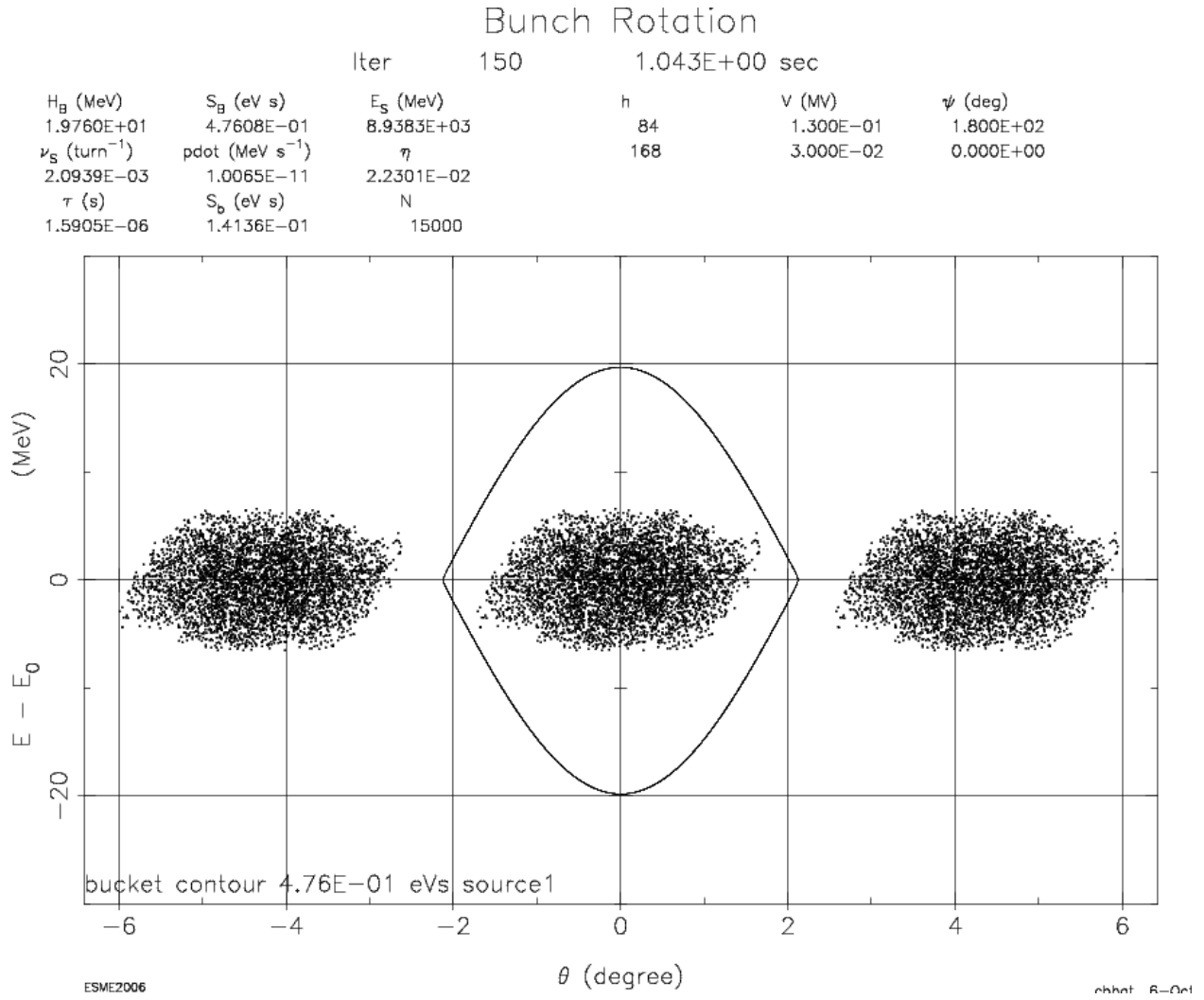


Figure 4c: Bunch rotation with $VRF(h=2)/VRF(h=1) \sim 0.23$. Rms energy spread = 2.85 MeV

This study clearly shows that the use of 2nd harmonic rf system for bunch rotation at extraction in the Booster we can meet the PIP/PIP-II beam energy spread <3 MeV to the Recycler for slip stacking even if the beam emittance in the Booster at extraction is significantly larger than 0.1 eVs.

Author would like to thank C.Y. Tan for many useful discussions about the 2nd harmonic rf systems which is being built for the Fermilab Booster.